NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Maryland 20034

COMPARISON STUDY OF ALUMINUM, FERRO-CEMENT, AND FIBER-REINFORCED PLASTIC FOR SMALL CRAFT IN KOREA

by

Benjamin Whang

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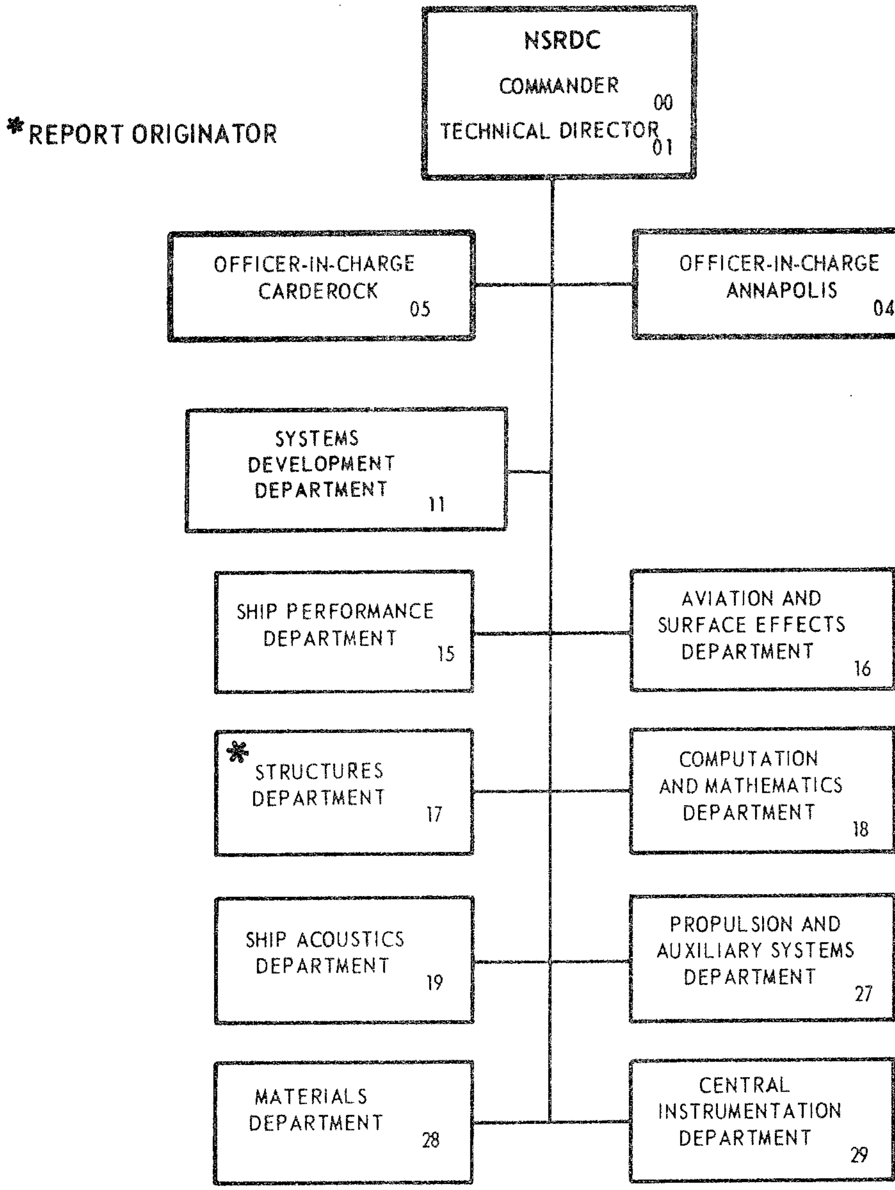

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ABSTRACT

This work compares aluminum, ferro-cement, and fiber-reinforced plastic in terms of small boat construction costs, strength-stiffness/weight characteristics, maintenance, fatigue, impact resistance, fire resistance, etc. within the framework of present day Korean technology and economics.

ADMINISTRATIVE INFORMATION

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ACKNOWLEDGMENTS

The author thanks Mr. Harry Rich, Science Advisor to Commander Naval Force Korea, for initiating the project and Messrs. A. Dinsenbacher, F. Brauer, J. Corder, and D. Harry for valuable discussions during the project.

The report is dedicated to the officers and men of the Korean Navy and to the workers at the Chinhae Naval Shipyard, Chinhae, Korea.

INTRODUCTION

In late 1971, the Commander Naval Forces Korea (COMNAVFORKOREA) sent a message to the Naval Ordnance Laboratory (NOL) indicating the interest of the Korean Navy in knowing the tradeoff between ferro-cement (FC), aluminum (AL), and fiber-reinforced plastic (FRP) for small craft construction. In February of 1972, the Naval Ship Research and Development Center (NSRDC) proposed a paper study to compare these materials. The study was authorized the following month under the Navy Science Assistance Program (NSAP).

This report attempts to compare the three materials in terms of construction costs, strength-stiffness/weight characteristics, maintenance, fatigue, impact, fire resistance, etc. within the framework of Korean technology and economics in the hope that the Korean Navy will find it useful in deciding which material to use for small craft construction.

The present work is essentially an extension of that by Spaulding[1] and Silvia[2] on material comparison; this presentation has been updated and modified for relevancy to the present day Korean Navy.

[1]Spaulding, K.R., Jr., "Structures," Univ. Michigan Lecture Notes on Small Craft Design, Vol. II, Chap. 5 (1969). A complete listing of references is given on page(s) 26.

[2]Silvia, P.A., "Structures," Univ. Michigan Lecture Notes on Small Craft Engineering (1971).

Much of the information used for the cost comparison was obtained recently either when the author was in Korea on an NSAP project concerning ferro-cement boats or subsequently through correspondence with the Navy Science Advisor to COMNAVFORKOREA.

Each material is described separately, the three are then compared, and a recommendation is made for selecting a hull material for small craft construction in Korea. Bibliographies on the three materials are given at the end of the report.

ALUMINUM

INTRODUCTION

Small boats have been in the forefront of the marine use of aluminum, and the U.S. aluminum industry has accrued more experience with the use of that metal for small boats than for any other type of hull.[2]

The history of aluminum boats goes back to 1891 when the Swiss built a 17-ft launch in Zurich. In 1895 the French built an aluminum torpedo boat which increased the speed of the vessel by over 3 knots, primarily because of reduced deadweight. Today yachts, sailboats, fishing boats, gunboats, hydrofoils, crewboats, supply boats, and air cushion and surface effect vehicles are made of aluminum and travel the inland and sea coasts of all five continents.

The Aluminum Association indicates that marine use totaled 50 million lb in 1968 and that about 60 percent of all pleasure craft (331,000) produced in the United States during 1969 were of aluminum.

MATERIAL

The principal ore of aluminum is bauxite which is first crushed and washed to remove the clay contents. Then the ore goes through a series of chemical treatments to become fine white alumina (Al_2O_3, aluminum oxide) precipitate. Next the alumina goes through an electrolytic smelting process in the presence of a catalyst (molten cryolite). Pure aluminum is then collected in the liquid state and cast into ingots. The ingots are later melted, alloyed, and hot- or cold-worked to obtain the desired temper and thickness. Extrusions are produced by forcing alloy billets through dies whose openings are patterned to suit the desired shape. In general, 4 lb of bauxite are required to produce 1 lb of pure aluminum.

PROPERTIES

Aluminum is popular for the following reasons:[3]

1. Light weight – it is about one-third as heavy as steel and offers a high ratio of horsepower to weight and either high speed or a reduction in power requirements.
2. Corrosion resistance – Marine aluminum hulls need not be painted because of the ever-present aluminum oxide film. (Some boats are painted for aesthetic reasons or for antifouling protection.)

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[3] Michalopoulos, C., "Aluminum Small Boat Design," Univ. Michigan Lecture Notes on Small Craft Engineering (1971).

3. Impact resistant – possessing high tensile strength and low modulus of elasticity (about one-third that of steel) aluminum offers large deflections which allow the hull to absorb high impact energy. Moreover, because of the ductility of aluminum, hulls are highly resistant to puncture.

Because of their improved corrosion-resistant characteristics in sea water the 5000 series alloys are the only alloys recommended for marine use.

Table 1 lists the specification properties of aluminum alloys as prepared by the U.S. Navy.[4]

TABLE 1 – SPECIFICATION PROPERTIES OF ALUMINUM ALLOYS

(From NAVSEC)[4]

Alloy	Ultimate Strength psi	Tensile Strength Yield psi	Allowable Working Stress	
			Shear psi	Tension & Compression psi
Plates:				
5042-H34	34,000	26,000	10,000	16,000
5086-H32	40,000	28,000	11,000	18,000
5454-H34	39,000	29,000	8,000	14,000
5456-H321	46,000	33,000	13,000	21,000
Shapes:				
5083-H111	40,000	24,000	10,000	16,000
5086-H111	36,000	21,000	8,000	14,000
5454-H111	33,000	19,000	8,000	14,000
5456-H111	42,000	26,000	10,000	17,000
Tubing:				
5086-H32	40,000	28,000	11,000	18,000
5086-0	35,000	14,000	8,000	13,000
Note: Modulus of elasticity (Young's modulus) is 10,300,000 psi.				

The three major aluminum alloys in use in the marine field today are 5086, 5456, and 5083. Reynolds Metals Company[5] recommends 5086 alloy in its new temper for plate (H16) and for extrusions (H11) primarily because of the toughness of that alloy *in the welded condition.* Moreover, because of its

[4]"Guide for the Selection and Use of Aluminum Alloys for Structure of Ships of the U.S. Navy," NAVSEC (Nov 1967).

[5]Brooks, C.L., "Aluminum-Magnesium Alloys 5086 and 5456-H116," Reynolds Metals Company (Aug 1970).

low magnesium content, 5086 is less susceptible to exfoliation (flaking caused by corrosion) than is alloy 5456. (Exfoliation problems have arisen in Vietnam with some small boats built of 5456 hull plate.)

WELDING

Since the welding of aluminum is relatively new in Korea, it may be worthwhile to discuss several important aspects of welding.

Either the metal inert gas (MIG) or the tungsten inert gas (TIG) process is employed to weld marine structures. TIG welding is ideal for piping and minor repairs whereas MIG welding is recommended for all structural work.

In general the strength of an aluminum weld is lower than that of the percent metal. A good strong weld requires good equipment, precleaning, proper filler metal, proper shielding, correct gas proportions, proper joint preparation, and well-trained personnel.

For MIG and TIG with a-c current, the shielding gas must be argon and for TIG with d-c current, it must be helium or a mixture or argon and helium (for example, 75 percent helium and 25 percent argon or other combinations that are suited to the thickness of the material, the welding position, the joint design, etc.) Pure argon is very economical and liquid argon is recommended for mass-produced hulls. The hose to be used for the shielding gas should not have been previously used for other gases or water.

Plates and structural members can be cut and their edges prepared for welding by mechanical means (sawing, machining, chipping, or sheaving). Metal surfaces must be cleaned of grease, oil, dirt, and machining or forging lubricants with a suitable solvent. They must also be free of tears, burrs, and anything else that would have an adverse affect on the quality of the weld.

Many detail structural deficiencies begin at crater cracks that slowly propagate into the weld or even into the parent metal. To avoid this, it is absolutely essential that the welder fill all craters to the full cross section of the welds by reversing the direction of travel before terminating the arc. Preheating is required only to remove moisture prior to welding. The temperature of the metal should not exceed 150 F.

Generally speaking, continuous welding should be specified for areas of high stress concentrations or vibrations since it minimizes the possibility of crater cracks. There are areas of a boat, however, where intermittent welding may be used to reduce weight or cost and such areas should be so specified. (It is the author's personal opinion that all welds should be continuous.)

Finally, fillet sizes for double continuous welds should not exceed the thickness of the thinner member that is being welded.

AVAILABILITY AND COST

Since aluminum is not made in Korea, the Korean Navy must import it either from Japan or the United States and pay an import tax of about 50 to 70 percent. This aspect, together with the fact that aluminum welding technology is just starting in Korea, must be taken into consideration when comparing aluminum to other materials that are also suitable for small boat construction.

FERRO-CEMENT

INTRODUCTION

Ferro-cement consists of several layers of wire mesh reinforcing in a mortar of sand and Portland cement. There is a tendency to compare the material to reinforced concrete, but actually it exhibits quite different properties. The basic differences in composition are that ferro-cement has a higher percentage of steel reinforcing by weight (over 15 percent) and that the reinforcing material is more evenly distributed through the material. The strength of the material is related to this weight and distribution of steel. A direct comparison may be made to fiber-reinforced plastic where the fiber and resin perform the same relative functions as the steel and cement in ferro-cement. Ferro-cement has proven particularly applicable to thin-walled structures in contrast to ordinary reinforced concrete which is better suited for thicker structures.

Ferro-cement has acceptable strength and stiffness, is waterproof, fireproof, corrosion-resistant, and its basic materials are very inexpensive. In addition the material lends itself readily to fabrication by semiskilled labor without expensive equipment or facilities. However, quality control is a major problem and the plastering operation requires considerable skill.

The history of ferro-cement is well documented.[6,7]

Lambot (France, 1849) patented the method under the name "Ferci-ment" and constructed a number of rowing boats. A ferro-cement boat was constructed in Holland in 1887 and is still in use on a pond at the Amsterdam Zoo. The process was revived in the early 1940's by Dr. P.L. Nervi (Italy) as "Ferro-cement," and several small craft were constructed in that country between 1943 and 1948. There was apparently no activity from 1948 and until 1961 when the process was simultaneously revived in New Zealand and in England.

The material was introduced into the United States and Canada between 1965 and 1967. Today at least seven firms in the United States and four in Canada are principally engaged in the production of ferro-cement barges and small craft. Ferro-cement craft are now also built in England, New Zealand, Australia, Russia, China, Thailand, Vietnam, Iran, South Africa, Span, France, and Korea.* Several hundred craft are in service including a number of small trawlers. The Nervi 38-ft ketch NENNELE, built in 1948, is reportedly still in service and in excellent condition.

*In Korea ferro-cement is known as "mesh-reinforced cement."

6Gardner, J. et al., "The Use of Ferro-Cement in Boat Building," International Marine Publishing Company, Camden, Maine (1967).

7Norris, C.F., "Why Not Ferro-Cement?," Marine Technology (Jan 1969).

COMPOSITION

The sand/cement ratio varies from 1.5:1 to 2:1. The water/cement ratio should not exceed 0.35; this is approximately 4 gal of water per bag of cement.

A sharp, fine grade of sand is used in ferro-cement; 100 percent must pass a No. 8 sieve and 10 to 15 percent must pass a No. 100 sieve. The cement is an alkali-resistant Portland cement, generally Type 5. Between 5 and 15 percent (of cement weight) of an amorphous silica (Pozzolan) is added to the cement weight for sand/cement/water ratios. It absorbs the free lime during the setting, resulting in a denser, stronger, more waterproof material with improved working qualities during plastering.

The steel reinforcement in ferro-cement commonly consists of a grid of 1/4-in. rod running fore and aft on 2- to 3-in. centers covered on each side with several layers of 19 and 20 gage 1/2-in. square or hex wire mesh. The number of layers of mesh is determined by maintaining the steel-reinforcing content of the material at between 24 and 36 lb/ft^3 (out of a total density of about 160 lb/ft^3). In some methods of construction, 3/4-in. pipe transverse frames are added. High-tensile wire has been used in place of the reinforcing bars, and expanded metal has been used in place of the wire mesh.

FABRICATION

Detailed descriptions of construction methods are available.[7-9] The problems of setting and curing, hull weight support, and continuous versus interrupted plastering are common to all fabrication processes. Before any work can be done following plastering, the ferro-cement must set for 8-12 hrs. Following this, a 3- to 4-wk drying period is required during which the hull must be kept constantly damp. Temperature must be maintained above freezing, and temperature variations due to drafts or sunlight must be avoided. Careful consideration must be given to supporting the entire hull weight during plastering and setting. Wet cement is very heavy, unless it is properly supported, the wire skeleton may sag before the cement is thoroughly set. Mortar that is too wet will flow out of the mesh. Continuous plastering of the entire structure is recommended. If the process is halted, an epoxy coating should be applied to the faying surface before plastering is resumed.

With careful planning, all main structural connections should be fabricated with the hull. Wooden plugs are set into the wire skeleton wherever openings and penetrations will be located. Bolted connections

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[8]Samson, J. and G. Wellens, "How to Build a Ferro-Cement Boat," Samson Marine Design Enterprises, Ltd. Ladner, B.C., Canada (1968).

[9]Whitener, J.R., "Ferro-Cement Boat Construction," Cornell Maritime Press, Cambridge, Md. (1971).

can be made, but a good bearing area should be provided on both sides through the use of stiff backing plates. A certain amount of probing with a drill (carbide tipped) may occur as the reinforcing bars are encountered. Deckhouses, entire decks (along with their supporting frames), and gunwales are generally made of wood.

Quality control is a serious problem with ferro-cement. Thorough mixing and the proper sand/cement/water ratio are critical. The final thickness and the quantity and distribution of reinforcement are also areas of concern. There is virtually no way to check these factors in the finished product. Control must be exercised at the time of fabrication.

Bonding wood to an already cured cement hull is not an easy task. It can be done by using a mixture of epoxy and sand (about 1:1 mix by weight) with wire mesh reinforcement. For example, in fabricating the Korean CRABS (cement riverine assault boats), a strip of wire mesh was bent in the form of an "L" and the mixture of sand and epoxy (S/E) was plastered onto both the web and the hull through the wire mesh (with S/E covering the wire mesh) in order to bond the web of a transverse frame to the cement hull. This is a slow process because the sand and quick-hardening epoxy must be mixed only in small batches. If the mix is too thin, it runs down from vertical surfaces, and if too thick, it gives weak bonding. The effectiveness of this bonding technique is yet to be proven. Periodic examination of the existing Korean CRABS should shed more light on this matter. In the meantime, other techniques should be investigated to improve the web/hull connection.

In the present state of the art, ferro-cement construction has several limitations. It is a relatively dense material at 160 $lb/ft.^3$ Although hulls have been built with thicknesses of less than 1/2 in., current construction averages over 3/4 in. This corresponds to an area density of approximately 10 $lb/ft.^2$ If the mortar mix is proper, the keys to good strength properties for ferro-cement are the type, quantity, and distribution of steel reinforcement. Both the surface area of the steel for adhersion and the total cross-sectional area for strength and stiffness are critical. There appears to be an upper limit to the cross-sectional area of the individual strands of steel reinforcements. This limit is related to the adhesive bond strength at the mortar/wire interface. It would seem that an optimum diameter for rods and mesh could be determined experimentally.

Another area of concern in ferro-cement is puncture resistance. Unlike impact resistance, puncture resistance is a localized effect caused when sharp objects hit the boat. Impact resistance of ferro-cement can be coped with by making the structure more flexible during the design phase. However, the puncture resistance of ferro-cement is quite low, as evidenced by the fact that during the repair of leaky areas it is very easy to chip out the cement with a sharp pick (sharpened out of a 1/2-in. reinforcing rod). In fact, several of the 12 leaky areas in CRAB-1 appeared to have been caused by sharp objects.

Although ferro-cement is essentially nonflammable, it is readily damaged by heat, resulting in spalling of cement and melting or annealing of the wire mesh near the surface.

Current practice in ferro-cement has not received the scientific analysis it deserves. Only recently has the scientific community begun to show interest in the material.[10-12] It is entirely possible that the material properties could be appreciably improved without undue cost. Also, the long-term effect of microcracks (which are unavoidable in any FC structure) should be investigated.

AVAILABILITY AND COST

Ferro-cement is said to be popular in the so-called "developing" countries like Korea mainly because of the low cost of materials and labor. It is true that the labor cost is much cheaper in developing countries. For example, the pay rate of an average Korean shipyard worker is about $0.25 (100 Won) per hour, and even with the overhead rate of about 200 percent, the labor rate is only $0.75 (300 Won) per hour. However, the cost of materials used in ferro-cement in Korea is another matter entirely. Ferro-cement hulls involve many materials, principally sand, cement, wire mesh, lumber, and epoxy. Sand is only $5/ton (about one-tenth its cost in the United States) and the cement produced in Korea costs $1.10/bag as opposed to $1.50/bag in the United States. Steel wire mesh (1/2-in. grid) used for CRABS in Korea costs about $18/100 ft^2 ($12/100 ft^2 in the United States). So far as the wood in a ferro-cement hull is concerned, a considerable portion is plywood which *is* made in Korea. However, since the raw material has to be imported, the cost of plywood is comparable to that in the United States. For example, a 4- x 8-ft sheet 3/4 in. thick (Douglas Fir, exterior) would cost $8.75 in Korea compared to $9.25 in the United States. A 3/8-in.-thick sheet on the other hand would cost $4.55 in Korea and $3.47 in the United States.

Epoxy is imported from the United States and the import tax is almost 100 percent. The cost is about $12/gal in the United States compared to $23/gal in Korea.

On the basis of the major items given above and estimates of the quantities of these materials used in a CRAB, a comparison of costs in the two countries is shown in Table 2.

TABLE 2 – FERRO-CEMENT MATERIAL COST COMPARISON

(All costs are given in dollars)

Material	United States	Korea
Sand and Cement	40	10
Wire Mesh	170	250
Lumber	170	200
Epoxy and Hardener	240	480
Total*	$620	$920

*Does not include hardware (nuts, bolts, and screws) or wood glue.

10 Brauer, F.E., "State-of-the-Art Survey of Ferro-Cement," NSRDC (Annapolis) Report S-529 (Jan 1971).

11 Shar, S.P. and W.H. Key, Jr., "Impact Resistance of Ferro-Cement," ASCE Proc., J. Struc. Div., Vol. 98, No. ST1 (Jan 1972).

12 Kar, J.N. and A.K. Pal, "Strength of Fiber-Reinforced Concrete," ASCE Proc., J. Struc. Div., Vol. 98, No. ST5 (May 1972).

It can be seen from the table, that mainly because of the cost of epoxy, the material cost for ferrocement is about 50 percent higher in Korea than in the United States.

FIBER-REINFORCED PLASTIC

INTRODUCTION

The term "fiber-reinforced plastic" refers to a two-or-more-component structural matrix composed of thermosetting liquid dispersed through fibers that are cured into a hard plastic by chemical action and heat. A more familiar term "fiberglass" refers to glass-reinforced plastic (GRP) where the reinforcement is *glass* fibers.

It is a well-known fact that because fiberglass does not "flow," it is very poor in resisting impact loads. To increase the impact strength of fiberglass, a new combination has recently been introduced wherein *polyester* fibers are added to act as energy-absorbing reinforcement.[13] Therefore, to include the polyester fibers, as reinforcement, the acronym "FRP" which has meant fiberglass-reinforced plastic thus far, is now revised to mean simply "fiber-reinforced plastic."

The fiber reinforcement is composed of very thin filaments and is available either as a felt-like mat or as a woven fabric. Successive layers of reinforcement are individually impregnated with resin prior to or during layup against a supporting form or mold of the desired shape. The resin is allowed to cure, forming a strong, rigid structural laminate with the exact shape and surface texture of the mold. The strength of the laminate is controlled by the number of plies and the type of reinforcement within a given thickness of laminate.

FRP was used initially for boat construction about 25 years ago by the U.S. Navy for personnel boats.[14] Since then, the Navy has continued to rely heavily on FRP for the construction of thousands of small boats from 12 to 50 ft in length, including landing craft, utility and personnel boats, line handling boats, and whaleboats. Perhaps the most famous Navy fiberglass boat is the 31-ft river patrol boat (PBR) which has seen extensive service in Southeast Asia.

The U.S. Coast Guard has employed FRP in the construction of a wide variety of utility and partol boats up to 40 ft in length. Recent examination showed that an early 40-ft FRP boat was in excellent condition after nearly 20 yr of continuous service, with no apparent degradation in structural properties.

The development of large fiberglass fishing trawlers began about 10 years ago in South Africa with the construction of a series of 63-ft-long pilchard trawlers. The success of these vessels led to parallel developments in the United States primarily in the shrimping industry.[15] The first such vessel, the 72-ft

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[13] McCorsley, C.C., "Encron Reinforcement of Polyester Laminates," American Enka Company (Feb 1972).

[14] Scott, R.J., "Fiberglass Reinforced Plastics," Univ. Michigan Lecture Notes on Small Craft Engineering (1971).

[15] Cobb, B., Jr., "Design Construction and Economic Considerations in Fiberglass Trawler Construction," Conference on Fishing Vessel Construction Materials, Montreal, Canada (Oct 1968).

trawler R.C. BRENT, was launched in Florida in 1968. Today, several builders are marketing FRP shrimp trawlers about 75 ft long, and although service experience with these boats is limited, it appears to be excellent. The largest FRP fishing trawler currently in production is a 93-ft stern trawler being built in Peru.

The development of FRP minesweepers was begun simultaneously in the early 1900's by the navies of the United States and Great Britain. The nonmagnetic nature of FRP makes it an ideal material for such a vessel since it is both lighter and lower in life-cycle cost than conventional wood construction. U.S. Navy studies[16] have indicated the feasibility of building FRP minesweepers up to about 190 ft in length and have led to the construction of a full-scale midship section which was recently tested for acoustic characteristics and shock resistance. The results of British studies and tests were so promising that a prototype 153-ft FRP minehunter is now under construction and is to be launched soon. When completed, it will be the largest FRP boat in existence.

FRP has been used for a number of other marine applications over the years, including submarine fairwaters and sonar domes, deckhouses, tanks, masts, hatch covers, buoys, etc.[17]

ADVANTAGES AND DISADVANTAGES

FRP has several advantages over other materials for small craft construction:[14]

1. Resistance to marine environment – FRP does not corrode, rot, or otherwise deteriorate when exposed to salt, air, or water for extended periods. It is equally unaffected by the fuels or pollutants that are often found in rivers and harbors. (However, FRP will become fouled with grass and barnacles as readily as wood or metal; thus it requires antifouling bottom paint in salt or brackish waters.)
2. Light weight – with proper design and control in the shop, FRP structures can be fabricated at about one-half the weight of equivalent ferro-cement structures and at about an equal weight to equivalent aluminum structures.
3. High strength – the inherent strength of FRP is quite high relative to its weight, and long exposure to salt water has little effect on its properties.
4. Seamless construction – FRP hulls are generally fabricated as a one-piece molding without seams or laps and thus are leakproof.
5. Chemically inert – FRP does not react to salt water or most chemicals, and it is not susceptible to electrolysis.
6. Ability to orient fiber strength – the nature of FRP reinforcement permits the fibers to be oriented in the direction of maximum stress, thus providing the designer with the ability to economically optimize strength-weight relationships to a greater extent than with metals.

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[16] Spaulding, K.B. and R.J. Della Rocca, "Fiberglass Reinforced Plastic Minesweepers," Trans. Society of Naval Architects and Marine Engineers (SNAME) Vol. 73 (1965).

[17] Gibbs and Cox, Inc., "Marine Design Manual for Fiberglass Reinforced Plastics," McGraw-Hill Book Company (1960).

7. Ability to mold complex shapes – FRP materials can be molded into a wide variety of complex shapes with relative ease and economy.

8. Flexibility – the low modulus of elasticity of FRP is beneficial in abosrbing energy from impact loads such as slamming. (However, this flexibility can also be a design constraint.)

9. Ease of maintenance – FRP structures are relatively easy to repair. The noncorrosive nature of FRP generally results in much lower hull maintenance for smaller craft. (The corresponding savings for larger hulls may be less since antifouling painting is required at the same intervals as for hulls of other materials.)

10. Durability – recent surveys of U.S. Navy and U.S. Coast Guard small boats indicated no degradation in laminate properties after as long as 15 years of service. With proper maintenance and reasonable ease, FRP boats would appear to have an indefinite life, although substantiating data are presently unavailable because the material is relatively new.

These advantages are offset by a number of potential problems, which must be considered in designing FRP boats:[14]

1. Stiffness – the modulus of elasticity of conventional FRP laminates is usually less than 2×10^6 (compared to 10×10^6 psi for aluminum). The use of unidirectional FRP laminates with a greater percentage of the glass oriented in the direction of the load can increase the modulus, but FRP is still at a disadvantage for deflection-critical applications.

2. Hull strength – although the basic short-term strength of FRP is quite satisfactory, its fatigue strength is generally low; this aspect must be considered in selecting design loads and safety factors. In addition, the notch toughness of FRP structures must be evaluated to determine the problems associated with stress concentrations, for example, at hatch corners, endings of stiffeners or decks, and other discontinuities. The low buckling strength of FRP also warrants consideration in evaluating the basic structural concepts.

3. Creep – FRP has a tendency to creep if subjected to long-term loading and if the laminate stresses are high.

4. Vibration – the low modulus of elasticity of FRP could lead to problems with structural vibrations, particularly in way of reciprocating machinery and propellers.

5. Abrasion – the abrasion resistance of FRP is less than that of metals. This necessitates the use of bumpers or chafing plates in areas where abrasive loads might occur.

6. Vulnerability to fire – the conventional FRP laminate is fabricated with a type of resin which is flammable and supports combustion with about the same intensity and flame spread rate as plywood. Fire-retardant types that are self-extinguishing after removal of the source of flame are available but they are still combustible to some degree, and the laminates rapidly lose strength at high temperatures. The fire-retardant resins also generate toxic fumes in the presence of fire.

PROPERTIES

Fiber-reinforced plastics are subdivided into three basic categories of structural materials: resins, glass fibers, and polyester fibers.[14]

Resins

The resins used in the construction of fiberglass boats are the thermosetting type which, once hardened, cannot be softened by the application of heat.

Basic Types. There are two basic types of resins, namely, polyester and epoxy. Under ideal conditions, epoxies have very high bonding strength, particularly to metals. However, polyesters are used almost exclusively in FRP boat construction for the following reasons:

1. They are less expensive.
2. They have adequate strength. Although epoxies will give higher strength laminates under controlled conditions, this potential is not as significant in field applications where the curing is at room temperature and without pressure.
3. Most epoxies have a tendency to lose viscosity as the heat of cure increases, and they will drain from vertical or inclined surfaces.
4. Polyester resins allow the use of the simplest and most versatile production techniques of all thermosets, and they do not present the personnel hazards that epoxies do.
5. Polyesters have good chemical resistance and somewhat better heat resistance than epoxies.

(Epoxies on the other hand possess superior abrasion resistance, less water absorption, greater bonding strength, and much lower shrinkage. In addition, they provide somewhat greater flexibility in imparting desired mechanical or resistance properties than do polyesters. However, these advantages are not considered sufficient to offset the disadvantages of epoxies, particularly with regard to cost.)

Rigidity. The use of flexible or semirigid resins has the potential for increasing the resistance of laminates to impact loads such as hull slamming. However, they offer relatively little advantage for primary hull structures mainly because of increased overall hull flexibility. Therefore general purpose resins are generally used for structural laminates.

Fire Retardancy. The polyester resins classed as fire-retardant do not support combustion when the source of flame is removed, and they are harder to ignite. In the presence of flame, fire-retardant resins generage chlorine gas which smothers the flame. They have not become popular in commercial boat construction because of much higher cost, slightly higher specific gravity, and the greater difficulty of layup. At this time, their use is required in all U.S. Coast Guard boats as well as lifeboats.

Air Inhibited versus Non-Air Inhibited. Polyesters are basically air-inhibited resins and will not cure fully in the presence of air. To effect cure in air, paraffin (wax) is often added to the resin; during curing, the wax floats to the surface of the resin and seals it from the air. Such resins, called non-air inhibited, are the most commonly used in boat production. The wax film presents potential problems either in bonding to the surface or in painting, and sanding or solvent washing is generally required to remove the wax.

Curing Cycles and Catalyzation. Fiberglass reinforcement and properly catalyzed resin can be cured to a hard structural laminate either by the application of heat from an external source or by the addition of an accelerator to the resin-catalyst mixture to produce sufficient internal heat to cure the laminate at room temperature. Heat cure has been used to produce small parts with superior physical properties on a mass-produced basis. The use of heat cure for larger layups such as boat hulls is generally impractical because of the rapid cure cycle, the cost of the heated molds, and the cost of large external power supplies.

For a cure at room temperature, the curing time of a resin is a function of the type and concentration of the catalyst and accelerator. By adjusting the percentages of catalyst and accelerator, the fabricator can adjust the curing period to provide adequate time for impregnation and layup of the reinforcement prior to the start of resin hardening. Gel times as short as 30 min are common for normal boat layups with laminate thicknesses of 1/2 in. or less. For thicker laminates, however, the heat of cure would be so great and the gel times so short that laminate distortion and poor quality would result. Accelerators and catalysts will work together only in certain combinations. The following combinations are most commonly used for layups of polyester resin:

Catalyst:	Methyl Ethyl Ketone Peroxide (MEK)
Accelerator:	Cobalt Naphthanate
Catalyst:	Cuemene Hydroperoxide
Accelerator:	Manganese Naphthanate

Glass Fibers

Thin glass filaments are drawn together to form continuous bundles known as strands and the strands are used to make various types of reinforcements such as cloth, woven roving, and mat. The glass filament used in boat hull construction is a lime-alumina borosilicate E glass of low alkali content and high chemical stability and moisture resistance. Reinforcements are generally sold in rolls, varying in width from thin 3- to 4-in. tapes up to as much as 6 ft. Successive layers of reinforcement are impregnated with resin until the desired thickness is achieved.

Cloth. Cloth is a plain, square, open-weave material used primarily in small boat construction for surfacing the exposed areas of hulls and superstructures and for repairing laminate defects. It improves appearance, but it is expensive and builds up thickness too slowly to be economical for general construction. The dry weight of the more commonly used cloths varies from 6 to 10 oz/yd.^{2} The latter weight requires about 40 or 50 plies or layers to build up a laminate thickness of 1 in.

Woven Roving. Woven roving reinforcements consist of flattened bundles of continuous strands woven into a heavy plain weave with a slightly greater number of strands in the "warp" direction (parallel to the length of the roll of material) than in the "fill" (perpendicular to the roll). Woven roving is commonly used as a reinforcement for marine applications. When layup is by the contact or hand layup molding method, woven roving has the following advantages:

1. Good drapability and handling characteristics.
2. Rapid buildup of laminate thickness.
3. Higher strength and stiffness than mat.
4. Directional physical properties for orientation in high stress areas.

The most commonly used woven roving for boat construction weighs 24 oz/yd^2 dry and consists of five bundles per inch of width in the warp direction and four bundles per inch in the fill direction. This material builds up thickness at the approximate rate of 25 plies/in. A lighter 18-oz roving is also used although to a lesser extent.

Mat and Chopped Strand. The chopped-fiber type of reinforcement is available (1) as a prefabricated mat made from short, randomly oriented chopped strands of fiberglass held together with a soluble resin binder or (2) as chopped glass strands that are mixed with resin and simultaneously deposited in the mold with a chopper-spray gun. Mat reinforcement has the following advantages:

1. Lower cost per pound and unit thickness than fabrics.
2. Homogeneous material with equal physical properties in all directions.
3. Good interlaminar bond because of the interlocking action of the fibers.
4. Moldable into more complex surfaces and shapes than fabrics.
5. Easy to wet out.

Preformed mats are available in weights of from 3/4 to 4 oz/ft^2 (note that mat weights are specified on a square foot basis rather than on a square yard basis). The most commonly used mat weighs 1-1/2 oz/ft^2 dry and builds up thickness at the rate of about 20 plies/in.

Mat laminates have a lower glass content than fabric laminates and a resulting lower strength and modulus of elasticity. Thus mat laminates must be thicker in order to have the equivalent properties of a fabric laminate.

GRP Composites. A composite fiberglass reinforcement consists of alternating plies of mat and woven roving. The plies may be layed up individually or as combinations of several plies sewn or bonded together. This composite reinforcement improves the interlaminar bonds between successive plies, reduces porosity, and allows several plies to be layed up at one time. In addition, the resultant weight-strength and weight-stiffness characteristics appear to be ideal for small boat hulls except where minumum weight is required for high performance. The most common such composite, 24-oz woven roving and 1 1/2-oz mat, builds up thickness at the rate of about 12 plies/in.. Such composites are used extensively in commercial small boat hull construction.

Polyester Fibers

Polyester is spun from polyethylene-tetrephthalate, a fully saturated long chain polymer, with no chemical cross-linking between the polymer chains. The chemical resistance properties of the fiber are due to the full saturation. Polyester is a tough polymer with high abrasion resistance, but it lacks the high modulus of a glass fiber.

The polyester fabric wets out in the layup process at a rate that is slightly slower than for fiberglass chopped strand mat but much faster than for woven roving. Because of the relative good drape of the fabric, conformability to relatively complex shapes presents little problem.

The use of a heat cutting system (such as a soldering gun with a heat cutting tip) enables complex shapes to be cut while the edge of the fabric is sealed. This means less waste and no traveling of the fabric. This is one advantage that cannot be achieved with fiberglass woven roving. Polyester fabric can be sheared by conventional scissors.

Polyester fiber has a density of 1.14 gm/cc, compared to one of 2.5 gm/cc for glass. Polyester will yield 1.8 times more volume than an equal weight of glass. Because of the difference in density, a laminate of polyester will have a fiber content that is 40 percent by weight compared to 50 percent for glass woven roving. A chopped strand fiberglass mat laminate will contain 25 percent fiber by weight. This means that 1 lb of resin will be used for 1 lb of fiberglass woven roving, for 1 lb of fiberglass chopped strand, 3 lb of resin will be used, and 1.5 lb of resin will be used for 1 lb of polyester.

Glass fiber laminates have high tensile strength and modulus but low thickness. Since the thickness is squared to compute the load-carrying capacity in bending, the relatively low thickness results in a low flexural load-carrying capacity. (The glass-reinforced laminates also have poor impact properties.)

Polyester-reinforced laminate has low tensile strength and modulus but it has high thickness because of its low density. The high thickness produces a high load-carrying capacity in bending but the deflection is also high; this results in a poor structure compared to fiberglass. The impact strength of a polyester-reinforced laminate is considerably higher than that of fiberglass.

Combinations of Glass and Polyester Reinforcements. The considerably different physical properties of the two reinforcing materials can be utilized in various combinations to give a laminate that is superior to either of them.[13] Combination laminates can be prepared that will exhibit equal flexural strengths, higher load-carrying capacity, and much higher impact resistance compared to present fiberglass systems of the same cost. Laminates can be designed to give any combination of desired physical properties by using the proper laminate sequence.

For convenience, the following abbreviations will be used:

PWR or P = polyester fiber woven roving

GWR or G = glass fiber woven roving

MAT or M = glass chopped strand mat

(X) = multiple of X where X may be P, G, or M

For example, the combination G(P)G indicates glass fiber woven roving and (GWR) designates a sandwich of several layers of polyester fiber woven roving (PWR). In another example, G(MP)MG indicates that GWR laminates are sandwiched between alternating layers of MAT and PWR; the last M in the combined form is for symmetry.

The following materials were used for purposes of comparison:

1. Polyester Woven Roving (PWR). The fabric weighed 21 oz/yd^2 and was 0.0530 in. thick.
2. Glass Woven Roving (GWR). The fabric was made from Owens Corning E glass roving, weighed 24.0 oz/ yd,^{2} and was 0.030 in. thick.
3. Glass Chopped Strand Mat (MAT). The mat sold commercially at 1.5 oz/ft^2 and was identifed by the code number Type 711. The type of glass was "E" with a filament length of 2.0 in. The average mat thickness was 0.052 in.
4. Resin. A general laminating polyester resin commercially available as M.R. 480 (W.R. Grace Company) was used. The cast resin had the following properties:[13]

Tensile strength	8.6 psi x 10^3
Tensile modulus	5.00 psi x 10^5
Flexural strength	12.0 psi x 10^3
Flexural modulus	0.44 psi x 10^3
Density	1.15 gm/cc
Impact strength (Charpy unnotched)	0.3 ft-lb/in.

Table 3 (based on McCorsley[13]) compares the properties of PWR, GWR, and MAT; it also includes a comparison of two common laminates of glass fiber woven roving and glass mat (G(MF)MG and GG(M)GG) with three promising laminates that include polyester woven roving. The comparison was based on approximately the same material cost per square yard of laminate ($\approx$ \$12).

The following characteristics are of primary concern in comparing various diameters for small craft hull design:

1. Flexural load, which is the load-carrying capacity of the laminate in bending and is associated with flexural strength of the laminate.
2. Stiffness, which is the slope of the load-deflection curve which is related to flexural modulus of the laminate.
3. Impact load, which is the amount of energy (in feet per pound) required to break a specimen.

The flexural tests reported by McCorsley[13] were conducted according to ASTM D790, which involves a simply supported specimen loaded at the midspan. The span was 8 in. and the specimen width was 0.5 in.

The impact test used was the unnotched Charpy type (ASTM D256). Normally, the energy is reported as foot pounds per inch of face width by using a standard 0.5-in.-thick specimen. However, McCorsley reports the total energy required to break a 0.5-in.-wide specimen with the full thickness of each laminate.

Several observations can be made from Table 3; *all apply to a given cost:*

1. GWR is very poor in all three catagories, namely, flexural load, impact, and stiffness. MAT is good in flexural load and stiffness, but is poor in impact resistance. PWR has the best impact resistance but is very poor in flexural load and stiffness.

2. G(MG)MG (a common laminate) is very weak in resisting impact. GG(M)GG is excellent in flexural load and stiffness but below average in impact resistance.

3. The impact resistance is considerably enhanced, for laminates with polyester fibers, especially GM(P)MG and G(MP)MG. GGM(P)MGG is excellent in flexural load but relatively poor in impact resistance and stiffness. GM(P)MG is excellent in impact but not too good in flexural load and stiffness. G(MP)MG appears to be good in all three categories.

The above observations are summarized as part of Table 4 which ranks 22 different laminates including the eight given in Table 3. Again the ranking in Table 4 is based on a cost of about $\$12/yd^2$ for each laminate; however, the ranking is not expected to alter considerably for other cost value.

The following recommendations are based on the rankings shown in Table 4:

1. GWR, MAT, and PWR should rarely be used.

2. If flexural load is of primary concern, GG(M)GG, GGM(P)MGG, or GGG(M)GGG may be used.

3. If impact load is of primary concern, GM(P)MG or G(MP)MG may be used.

4. If stiffness is of primary concern (which is usually the case with FRP), GG(M)GG or G(MP)MG may be used.

5. For an all-around laminate, G(MP)MG is recommended.

AVAILABILITY AND COST

FRP industry is just beginning to grow in Korea, as evidenced by the fact that fiberglass row boats, canoes, bath tubs, etc. are being made commercially; moreover, fiberglass patrol boats (6-ton, 11-meter) were recently made for the Korean Navy. Thus Korea has the technique for working with single-skin laminates. However, the main difficulty at the present time is that FRP woven rovings must be imported and since these are classified as textiles, the import tax is 100 percent.

Furthermore, Korea is not presently prepared for sophisticated sandwich construction techniques (to increase stiffness to weight ratio) that use core materials such as polyurethane foam, balsa, polyvinyl chloride foam, and honey comb (made of paper, aluminum, fiberglass, etc.). The main difficulty with the sandwich system even in the United States is the high cost of core materials along with the associated problem of quality control in bonding the core material to the faces (or laminates). Therefore, only single-skin construction will be considered in the subsequent comparison of the three materials.

TABLE 3 – PROPERTIES OF FRP LAMINATES

(Approximate cost of all laminates is $12 per square yard)

	GWR	MAT	PWR	G(MG)MG	GG(M)GG	GGM(P)MGG	GM(P)MG	G(MP)MG
Layers	10	12	9	11	11	10	10	11
Thickness (in.)	0.300	0.624	0.480	0.440	0.500	0.435	0.485	0.530
Weight $(lb/yd)^2$	30.0	40.5	29.5	34.9	35.6	31.8	32.4	35.9
Flexural Strength (ksi)	41.9	19.2	15.1	31.6	33.1	41.2	25.0	28.4
Flexural Load (lb)	157.0	312.0	145.0	225.0	345.0	325.0	245.0	332.0
Impact Load (ft-lb)	16.0	21.5	46.0	18.0	29.0	33.0	46.00	42.0
Stiffness (lb/in.)	227	960	221	606	834	591	595	813
Material Cost $(dollars/yd)^2$	12.00	12.15	12.07	12.65	11.89	12.19	12.48	12.81

TABLE 4 – PROPERTY RANKING OF FRP LAMINATES

(Approximate cost of all laminates is $12 per square yard)

Ranking	Flexural Resistance	Impact Resistance	Stiffness
1	GG(M)GG	PWR	MAT
2	GGM(P)MGG	GM(P)MG	GG(M)GG
3	GGG(M)GGG	G(P)G	G(MP)MG
4	MAT	G(MP)MG	GGG(M)GGG
5	(G)4M(G)	MGM(P)MGM	GMM(P)MMG
6	G(MP)MG	M(PM)PM	G(MG)MG
7	GMM(P)MMG	MG(P)GM	M(PM)PM
8	MGM(P)MGM	GMG(P)GMG	GGM(P)MGG
9	G(MG)MG	GMM(P)MMG	MGM(P)MGM
10	(G)6P(G)	GGM(P)MGG	(G)6P(G)
11	GM(P)MG	GGG(M)GGG	GM(P)MG
12	(G)5P(G)	GG(M)GG	(G)4M(G)
13	GMG(P)GMG	(G)6P(G)	GMG(P)GMG
14	GG(P)GG	(G)5P(G)	(G)5P(G)
15	G(P)G	GG(P)GG	(G)4P(G)
16	G(PG)PG	G(PG)PG	GGG(P)GGG
17	(G)4P(G)	(G)4M(G)	GG(P)GG
18	GGG(P)GGG	(G)4P(G)	G(P)G
19	MG(P)GM	MAT	MG(P)GM
20	M(PM)PM	GGG(P)GGG	G(PG)PG
21	GWR	G(MG)MG	PWR
22	PWR	GWR	GWR

COMPARISON OF AL, FC, AND FRP

The selecting of a hull material for a particular boat is not a simple task. First of all, most boat designers and builders are biased in one way or another mainly because of past experience with certain materials. Second, each material is best for *some* application, and no material is best for *all* purposes. A truly objective procedure for selecting a hull material must involve a complete feasibility study that considers the cost and weight of each material for a particular application. One must balance the advantages of each material against its disadvantages and make a *judgment as to which material is "best" for a particular purpose.* The following paragraphs are given to aid in the decision-making process.

MECHANICAL PROPERTIES

Table 5 summarizes the mechanical properties of aluminum (AL), ferro-cement (FC), and fiber-reinforced plastic (FRP). In this comparison, alloy 5086 was selected to represent aluminum and two types of steel wire mesh were selected to represent ferro-cement, namely, galvanized and ungalvanized.* For fiber-reinforced plastic, GWR laminate and a common G(MG)MG combination were chosen as glass laminates and G(MP)MG was selected as a laminate with polyester woven roving.

It should be pointed out that aluminum has a distinct yield point beyond which it can still carry more loads while taking permanent distortion. Glass fibers, on the other hand, are not ductile and have no yield points although those laminates with polyester woven roving would show ductility after glass fibers break. Ferro-cement does have an apparent yield point (mortar cracking in tension); the material continues to carry more load to a point of excessive increase in deflection which is defined as the ultimate strength.

Also, since bending is the primary consideration in small craft design, other properties such as tension, compression, shear, etc. are not compared here.

One obvious thing to note in Table 5 is that so far as the ratio of strength-stiffness to density is concerned, aluminum is the best material and ferro-cement the worst.

Table 6 is an attempt to compare the weight of hulls built of the various materials; aluminum is used as the reference. Each material is assumed to be in the form of a beam of rectangular cross section of unit width.

The final thickness of a panel is usually governed either by the highest stress or by the maximum deflection. The deflection of a panel for a given configuration and load is a function of thickness cubed multiplied by modulus of elasticity. On this basis, calculations were made of the thickness of the various materials required to attain the same deflections as an aluminum panel.

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*The ungalvanized wire, as drawn, has a tensile yield strength of 130 ksi. This high yield strength is annealed out by preheating and hot dipping which occur during the galvanizing process, and the yield strength of the galvanized wire is reduced to 53 ksi.

The fact that stress is a function of thickness squared was used (as can be seen in the second row of Table 6) to compare the thickness required to keep the various materials within their safe stress limits. Note that compared to aluminum, FRP is deflection-limited and FC is strength-limited. The structural weights required for "equally sound" structure (with a reference of 100 for aluminum) were obtained by multiplying the relative thicknesses (controlled either by deflection or strength) by the material densities. These values were used as a structural weight index when the cost of hulls of the various materials were compared (Table 7). It should be pointed out here that so far as the hull weight is concerned, there is no doubt that FC is the worst of the three materials (even with the ungalvanized wire mesh).

COMPARATIVE MATERIAL AND LABOR COSTS

Table 7 compares the cost of material and labor; this is probably the most important consideration in selecting a hull material. The cost figures are based on about three hulls.

As has already been mentioned, AL is brought into Korea at an import tax of about 60 to 70 percent and since FRP woven roving is classified as a textile (textiles are one of Korea's protected industries) the import tax is about 100 percent. Mainly because of the cost of epoxy, ferro-cement is about 50 percent more expensive in Korea than in the United States as indicated by the first row of Table 7. The estimates of productivity (hours of labor per pound of material) given in Row 2 are based on the fact that aluminum welding is relatively new in Korea and that FRP technology is just starting there. The productivity rate for ferro-cement is relatively accurate and is based on the recent experience of the Korean Navy with the CRAB project.

Productivity for the United States is based on published commercial rate. Wages in Korea are much lower than in the United States, and at the present time, an aluminum worker in Korea would not necessarily be paid any more than a ferro-cement worker (Row 3). The material and labor cost (Row 5) indicates that FC is cheaper than FRP and AL by factors of about 2 and 4, respectively. However, as was indicated in Table 6, FC is the heaviest of the three materials (Row 7), and the net effect is that the structural cost of FC and FRP in Korea are respectively about 58 and 65 percent that of AL. It is interesting that despite the drastically different rates of productivity and labor, a similar conclusion can be made regarding structural costs in the United States (see Row 8).* Rows 9 through 11, which are based on the material and labor cost of aluminum in the United States as the reference, show that it is cheaper to

*A note of caution: For Rows 6 through 8, the values for Korea should not be compared with those for the United States since the reference for indexing is different in each case. For example, in the case of FC, the structural cost index of 58 in Korea should not be compared with 64 in the United States.

TABLE 5 – MECHANICAL PROPERTIES OF THE THREE MATERIALS

Property	AL	FC		FRP		
	5086	Galvanized	Ungalvanized	GWR	G(MG)MG	G(MP)MG
Density ρ, lb/ft^3	166	160	160	133	106	99
Flexural Modulus E, ksi x 10^3	10.4	3.7	7.1	2.2	1.8	1.4
Flexural Strength σ, ksi	40	3.0	8.7	40	32	28
Flex. Mod/density E/ρ	0.0626	0.0231	0.0444	0.0165	0.0170	0.0156
Nondimensional E/ρ	100	37	71	26	27	25
Flex. Str./Density σ/ρ	0.241	0.019	0.054	0.300	0.302	0.283
Nondimensional σ/ρ	80	6	18	99	100	94
Strength-Stiff./Density $(\sigma + E)/\rho$	180	43	89	125	127	119
Nondimensional $(\sigma + E)/\rho$	100	24	50	70	71	69

TABLE 6 – STRUCTURAL WEIGHT OF THE THREE MATERIALS

Criterion	AL	FC		FRP		
		Galv.	Ungalv.	GWR	G(MG)MG	G(MP)MG
Thickness for equal deflection $T_x = (E_a/E_x)^{1/3}$	1.00	1.48	1.14	1.68	1.79	1.93
Thickness for safe flexural strength $T_x = (\sigma_a/\sigma_x)^{1/2}$	1.00	4.47	2.14	1.00	1.12	1.20
Weight for "equally sound" structure*	100	4.32	207	134	114	115
$100\ T_x\ \rho_x/\rho_a$		Strength-sensitive design		Deflection-sensitive design		

*Without considering impact strength.

TABLE 7 – COMPARATIVE MATERIAL AND LABOR COST

(All costs are shown in dollars and are based on about three hulls)

	Factors Considered in the Comparison	Korea AL 5086	Korea FC Ungalv.	Korea FRP G(MP)MG	United States AL 5086	United States FC Ungalv.	United States FRP G(MP)MG
1	Material Cost, per pound	1.10	0.27	0.75	0.70	0.18	0.50
2	Productivity, hour/pound	1.70	0.37	0.60	0.16	0.07	0.08
3	Wages per hour plus Overhead	0.80	0.80	0.70	10.00	6.50	12.20
4	Labor Cost per pound of Material (Item 2 x Item 3)	0.96	0.30	0.42	1.60	0.45	0.98
5	Material and Labor Cost per pound of Material (Item 1 + Item 4)	2.06	0.57	1.17	2.32	0.73	1.48
6	Material and Labor Cost Index	100*	28	57	100**	31	64
7	Structural Weight Index	100	207	115	100	207	115
8	Structural Cost Index (Item 6 x Item 7/100	100	58	65	100	64	74
9	Material and Labor Cost Index	89	25	50	100***	34	64
10	Structural Weight Index	100	207	115	100	207	115
11	Structural Cost Index	89	52	57	100	64	74

*Based on 2.06 in Row 5.

**Based on 2.32 in Row 5.

***Based on 2.32 in Row 5 for both countries.

TABLE 8 – COMPARISON OF CRAB-LIKE BOATS IN KOREA

(All cost items are in dollars)

Factor	ARAB	CRAB	GRAB
Hull Weight, lb	1900	4100	2280
Material Cost	2180	1110	1710
Labor Cost	1900	1230	956
Structural Cost	4080	2340	2666
Engine Cost (for equal speed)	1550	3200	1780
Combined Structural and Engine	5630	5540	4446

use all three materials in Korea than in the United States. When aluminum becomes no longer an imported item and when Korea can make woven rovings, the costs of these materials should decrease substantially. Also, when the wood-to-FC connection is improved so that epoxy is not necessary or when Korea is able to produce epoxy, the material cost of FC should be reduced considerably. The productivity rate in Korea should change considerably over the next few years as experience is gained with these materials.

In addition to the structural cost, the cost of the engine plus the installation must also be considered in the tradeoff. In the case of the CRAB project, the structural cost was about $2340 per boat and that of the two outboard engines (Chrysler 105) about $3200! For the same speed, lighter boats would require smaller and cheaper engines and lower fuel consumption.

As a hypothetical case, assume that CRAB-like boats are to be made in Korea of aluminum (ARAB) and fiberglass (GRAB). Table 8 gives estimates of structural cost plus engine cost (assuming that size and cost of the engine are directly proportional to the weight of the hull). The pronounced superiority of GRAB over both ARAB and CRAB is obvious for the hypothetical case.

OTHER IMPORTANT CONSIDERATIONS

Other important considerations are difficult to assess quantitatively but must not be ignored in making a judgment on which hull material to select for a particular purpose; resistance to impact, fatigue, and fire; repair and maintenance; and expected life.

Impact Resistance

Impact can cause cracks, dents, or holes and usually the impact resistance to large impacts, punctures, and cracks. Stress concentrations are less critical since plastic deformation redistributes the stresses. However, aluminum would dent long before FRP would begin to crack. Ferro-cement is probably the worst of the three materials so far as resistance to local punctures is concerned because the mortar chips off very easily when subjected to minor impact by sharp objects.

Fatigue Resistance

Fatigue is an important consideration for small boats because of bottom slamming. The fatigue strength (endurance limit) of a material is the level to which it may be stressed many times without failure. As the number of loading cycles increases, the allowable stress decreases and eventually becomes asymptotic to the endurance limit of about 10^8 cycles. The endurance limits of the three materials are:

Material	Limit (psi)
AL 5086 unwelded	8
FC ungalvanized	3*
FRP:	
GWR	8
G(MP)MG	Not yet available

*Unpublished results of tests by Brauer at NSRDC Annapolis.

Welds may reduce the fatigue life of aluminum considerably, in some cases to as low as 2 ksi. However, it should be stated that up to a load cycle of 10^6, the allowable stress for aluminum is much higher than that of FRP or FC.

Fire Resistance

Fire constitutes a serious threat to small craft. A ferro-cement hull is essentially fireproof although heat damage may result in spalling of mortar and melting or annealing of wire mesh near the surface of ferro-cement. Aluminum distorts and melts at a relatively low temperature. FRP is the worst in fire resistance. Fire-retardant resins are available and are used in the construction of all Navy and large Coast Guard FRP craft. Fire-retardant resins have a slightly higher specific gravity than ordinary resins and cost roughly twice as much.

The use of fire-retardant resins produces a laminate which is "self-extinguishing" rather than fire "proof." These laminates will burn much as a nonfire-retardant laminate when an external flame source is applied. However, when the heat source is removed, a fire-retardant laminate will extinguish itself whereas other resins will continue to burn.

Repair and Maintenance

The ease of repair and the cost and availability of repair materials, labor, and facilities are of concern. Ferro-cement is the easiest and cheapest of the materials to repair, but recent experience in Korea indicates that it is certainly not the fastest to repair. FRP has proven to be easily and quickly repairable with simple repair kits (if available) or readily available materials, but shelter and some degree of temperature control are required.

Aluminum is readily repairable when welding facilities are available, but aluminum facilities are not yet plentiful in Korea.

In the area of maintenance, both the amount and the frequency of maintenance are of concern. Reliable statistics on craft maintenance costs are almost nonexistent, but this writer would list the materials from best to worst as fiberglass, aluminum, and ferro-cement.

Expected Life

The expected life of a craft depends on its use, its durability, and the maintenance it receives. In theory, any craft could be made to last forever. In practice, there is a point of diminishing returns where it is cheaper to replace the craft than to continue to meet increasing maintenance costs.

Both wood and steel craft are subject to decomposition; without adequate maintenance, their average life expectancy is definitely limited. Craft constructed of the materials described herein are expected to have on the average, a higher life expectancy than those of wood or steel, although they have not been in use long enough to provide any statistical evidence. The author's subjective guess is that aluminum would have the best life expectancy followed by FRP and then ferro-cement.

CONCLUSIONS AND RECOMMENDATIONS

An attempt has been made here to look at all of the important factors that affect material selection. No simple conclusion as to the "best" choice has evolved. In fact, each material is best for some particular application, and it is up to the designer to examine each design on an individual basis. In the final analysis, the design itself is the key. A given material for a single design will be best in some respects and poor in others. Where the material is deficient, it is all the more important that the design compensate for these deficiencies.

However, Table 9 should be helpful *if one is forced to make a selection without a particular application in mind.* The table gives a series of rankings of the materials for various attributes, and the material with the highest score is the most suitable overall. If some particular attribute is more important than another, its ranking may be multiplied across the board by some factor appropriate to its status. If all the attributes are considered of equal importance, FRP is the best, followed by aluminum and then ferro-cement. If the material and labor cost plus the weight factor are the only consideration, FC is the best followed by FRP and then AL.

TABLE 9 – RANKING OF THE MATERIALS FOR USE IN SMALL CRAFT CONSTRUCTION

(3 is the highest and 1 the lowest ranking)

Attributes	Aluminum	Ferro-Cement	Fiber-Reinforced Plastic
Material Cost	1	3	2
Labor Cost	1	3	2
Light Weight	3	1	2
Impact Resistance	3	1	2
Fatigue Resistance	2	1	3
Fire Resistance	2	3	1
Repairability	1	3	2
Maintenance	2	1	3
Expected Life	3	1	2
Equally Weighted Total	18	17	19

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13. ABSTRACT

This work compares aluminum, ferro-cement, and fiber-reinforced plastic in terms of small boat construction costs, strength-stiffness/weight characteristics, maintenance, fatigue, impact resistance, fire resistance, etc. within the framework of present day Korean technology and economics.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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